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Geospace Plasma Dynamics: Final Report (2002-2007)

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This technical report has been reviewed and is approved for publication.

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14. ABSTRACT
Radar measurements of backscatter from plumes extending above the bottomside spread-F layer correlated well with observations of equatorial plasma bubbles in quiet conditions, with lower correlation between scintillation and observations of plasma bubbles. DMSP satellites and the ROCSAT-1 satellite showed significantly fewer occurrences of plasma bubbles than expected near the west coast of South America, and an east-west chain of GPS receivers confirms a steep longitudinal gradient in EPB occurrence rates. A statistical database of equatorial plasma bubbles has been compiled. Observations of transient sheets of field-aligned currents observed by DMSP during the main phase of a magnetic superstorm showed that under some highly stressed conditions, contributions from low energy electrons and precipitating ions contribute significantly to Pedersen conductances. We developed a new fluid theory for the auroral return-current region in the guiding-center and gyrotropic approximation, and used in calculations of the turbulent heating rate for magnetospheric ions in downward Birkeland Current regions. We compared different theoretical descriptions of linear equatorial plasma instabilities, and showed that the ballooning mode description gives a physically more accurate and complete description and thus should be adopted for calculating linear growth rates. Our study of the unstable Rayleigh-Taylor plasma modes in the equatorial ionosphere has shown that the magnetic field fluctuations are associated with the shear Alfven waves, and that the electrostatic assumption is usually justified. Assimilating the vertical drift of the plasma after sunset can improve forecasts of equatorial radio scintillation.

15. SUBJECT TERMS
Equatorial plasma bubbles; Ionospheric plumes; Magnetized plasma, inhomogeneous; Space plasma physics; Nighttime equatorial plasma; Equatorial scintillations

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CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

The main research objectives of the AFOSR basic research task titled "Geospace Plasma Dynamics" were (1) to investigate solar wind-magnetosphere-ionosphere coupling processes, and (2) to specify and predict magnetospheric and ionospheric properties for Air Force systems applications. The research topics were chosen accordingly. The research efforts involved the analysis of satellite and ground-based data and the development of first-principles, physics-based theories and models that explain the data. The goal was to develop an improved capability to specify space weather at both high and low latitudes and to predict its effect on Air Force Command Control Communication Intelligence Surveillance and Reconnaissance (AF C3ISR) systems.

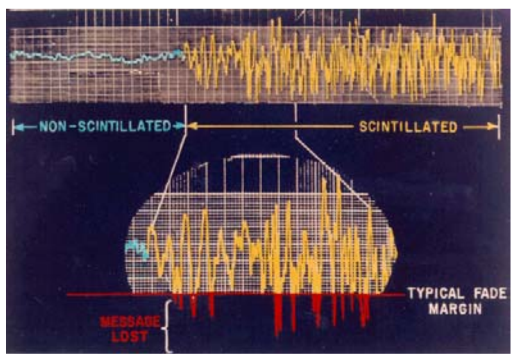

Figure 1. Example of Scintillation Outage Caused by Ionospheric Plasma Turbulence.

During the task period, we have worked on a variety of research topics including (1) global electrodynamics during magnetic storms; (2) general fluid theory for the Birkeland current system of the Earth's magnetosphere; (3) impact of storms on the ionosphere; (4) linear and nonlinear plasma processes in the equatorial ionosphere; (5) forecast model for equatorial scintillation; and (6) theory of the penetration electric field. In this final report we summarize major research accomplishments of the task. Details of these research efforts may be found in the

associated journal articles referenced in the report. Other research accomplishments during the task period will be evident from the list of all publications by the task members, which is given as an Appendix of this report. Each of these research accomplishments directly supports the C/NOFS satellite program, the DMSP satellite program, the GPS system, or the SPACE-BASED RADAR program, and is also related to the New World Vista objective of SPACE SITUATIONAL AWARENESS.

2. SUMMARY OF SELECTED MAJOR RESEARCH ACCOMPLISHMENTS

2.1 Multipoint Observations of Equatorial Plasma Bubbles [*Burke et al.*, 2003]

We compared evening sector measurements by the Jicamarca Unattended Long-term studies of the Ionosphere and Atmosphere (JULIA) radar, the Ancon scintillation monitor, and the plasma density sensors on Defense Meteorological Satellite Program (DMSP) satellites. During more than half of the 110 nights of JULIA operations in 1998 and 1999, backscatter was observed from plumes extending above the layer of bottomside spread *F*. On 98 % of the nights with no plumes, the S_4 index measured at Ancon was < 0.8. On ~90 % of nights with plumes, the value of S_4 exceeded 0.8. DMSP F14 crossed the magnetic equator within 7.5° longitude of Ancon near the 2100 local time (LT) meridian on 61 nights. During 32 overpasses, DMSP detected no equatorial plasma bubbles (EPBs) and JULIA detected no plumes. DMSP encountered EPBs on only 9 of the remaining 29 nights when JULIA observed plumes. Two plumes detected by JULIA on 15 April 1999 did not coincide with nearby EPBs crossed by the two satellites on the same evening. We also compared the seasonally averaged percent of nights with $S_4 \geq 0.8$ at Ancon with the percent of orbits in which a DMSP satellite detected EPBs. Data were accumulated between May 1994 and the first quarter of 2001. On a global scale at solar

minimum, DMSP encountered very few EPBs. In years near solar maximum the two data sets were well correlated. However, there were more nights with $S_4 \geq 0.8$ at Ancon than EPB encounters by DMSP satellites. This discrepancy reflects the effects of different sampling intervals and the fact that about a third of the plumes fail to reach the DMSP altitude. Still, a correlation coefficient of 0.88 indicates that EPB detection at 840 km is a good indicator that scintillation activity is occurring near the spacecraft's longitude at the Earth's surface. The data also suggest that bubbles are often generated in bursts rather than at relatively uniform intervals.

2.2. Longitudinal Variability of Equatorial Plasma Bubbles Observed by DMSP and ROCSAT-1 [*Burke et al.*, 2004]

We compared observations of equatorial plasma bubbles (EPBs) by polar-orbiting satellites of the Defense Meteorological Satellite Program (DMSP) with plasma density measurements from the Republic of China Satellite (ROCSAT-1) in a low-inclination orbit. DMSP data were acquired in the evening sector at low magnetic latitudes between 1989 and 2002. ROCSAT-1 plasma densities were measured in March and April of 2000 and 2002. Observations of individual EPBs detected by both ROCSAT-1 and DMSP were well correlated when satellite orbital paths crossed the same longitude within approximately ±15 min. We compiled a statistical database of ROCSAT-1 EPB occurrence rates sorted by magnetic local time (MLT), magnetic latitude, and geographic longitude. The rate of ROCSAT-1 EPB encounters at topside altitudes rose rapidly after 1930 MLT and peaked between 2000 and 2200 MLT, close to the orbital planes of DMSP F12, F14, and F15. EPB encounter rates have Gaussian distributions centered on the magnetic equator with half widths of ~8^{o}. Longitudinal distributions observed by ROCSAT-1 and DMSP are qualitatively similar, with both showing significantly fewer occurrences than expected near the west coast of South America. Figure 2

shows the occurrence rate of EPBs at each longitude for each month. A chain of GPS receivers extending from Chile to Colombia measured a west-to-east gradient in S4 indices that independently confirms the existence of a steep longitudinal gradient in EPB occurrence rates. We suggest that precipitation of energetic particles from the inner radiation belt causes the dearth of EPBs. Enhancements in the post-sunset ionospheric conductance near the South Atlantic Anomaly cause a decrease in growth rate for the generalized Rayleigh-Taylor instability. Results indicate substantial agreement between ROCSAT-1 and DMSP observations and provide new insights on EPB phenomenology.

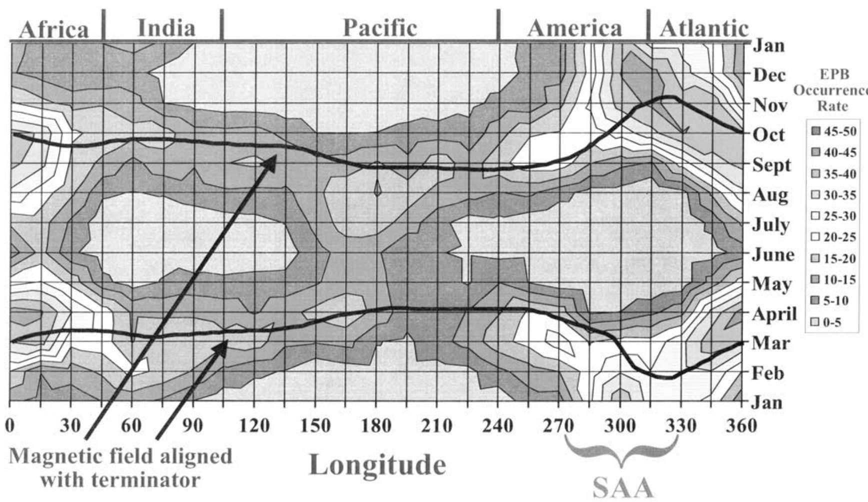

Figure 2. Contours of Equatorial Plasma Bubble (EPB) Occurrence Rates Measured by DMSP Satellites Between 1989 and 2002 Plotted on a Month versus Longitude Grid in Nine 5% Increments.

2.3. Transient Sheets of Field-Aligned Current Observed by DMSP during the Main Phase of a Magnetic Superstorm [*Huang and Burke*, 2004]

During the main phase of the April 6, 2000 magnetic storm with Dst ≅ –300 nT, four Defense Meteorological Satellite Program (DMSP) satellites encountered intense sheets of field-aligned currents (FACs). Their magnetic perturbations were > 1300 nT, corresponding to

integrated currents $|J_{||}| > 1$ A/m. The FACs appeared in both the evening and dawn magnetic local time sectors. They had relatively fast rise times (~5 minutes), lasted for ~0.5 hr, and were associated with widespread reconfigurations of plasma in the near-Earth magnetotail. The largest magnetic and related electric field perturbations occurred at magnetic latitudes < 60^o. Magnetometer measurements from DMSP satellites show repeated episodes of similarly large FACs late in the main phase of this and other superstorms. Poynting flux calculations indicate that a few percent of the total ring current energy is dissipated as Joule heat in the mid latitude ionosphere during each of these events. A survey of ground magnetometers at auroral and middle latitudes found perturbations typically < 200 nT, incommensurate with magnetic observations at the altitude of the DMSP satellites. The small ground responses reflect weak ionospheric Hall currents and provide an empirical validation of the theorem derived by Fukushima. Height-integrated Pedersen conductances (Σ_P) calculated with observed precipitating electron fluxes have significantly lower values than those estimated from Ohm's law using simultaneously measured electric and magnetic field variations. This discrepancy suggests that under some highly stressed conditions the neglect of contributions from low energy electrons and precipitating ions can lead to serious underestimates of Σ_P and a consequent misunderstanding of the magnetosphere-ionosphere circuit.

2.4. A Climatology of Equatorial Plasma Bubbles from DMSP 1989 – 2004 [*Gentile et al.*, 2006]

After examining evening sector plasma density measurements from polar-orbiting Defense Meteorological Satellite Program (DMSP) spacecraft for 1989 - 2004, we have established a statistical database of more than 14,400 equatorial plasma bubble (EPB) observations. EPBs are

irregular plasma density depletions in the post-sunset ionosphere that degrade communication and navigation signals. In general, the DMSP observations support Tsunoda's hypothesis that EPB rates peak when the terminator is aligned with the Earth's magnetic field, but unpredicted offsets are also evident in many longitude sectors. Plots of EPB rates for solar cycle phases: maximum 1989-1992 and 1999-2002, minimum 1994-1997, and transition years 1993, 1998, and 2003 reveal significant differences in the climatologies for solar maximum and minimum, between the two solar maxima, and in the transition years. To assess local time effects on EPB rates we also compare observations from F12, F14, F15, and F16 at slightly different post-sunset local times for 2000-2004. This study was undertaken to facilitate improvements in ionospheric models in preparation for the Communication/Navigation Outage Forecasting System (C/NOFS) mission.

2.5. Gyrotropic Guiding-center Fluid Theory for Turbulent Inhomogeneous Magnetized Plasma [*Jasperse et al.*, 2006]

Magnetospheric disturbances affect ionospheric properties at high latitudes, such as the electron density profile (EDP) and the total electron content (TEC). The magnetosphere drives perturbations in the ionosphere that, in turn, affect AF communications (HF), navigation (GPS) and surveillance (SBR) systems. When the magnetosphere is disturbed, it induces plasma-wave activity (turbulence) in the ionosphere through the field-aligned (Birkeland) current system. Figure 3 is a schematic diagram of the current system. Ions, electrons and neutral particles are heated, electron density profiles (EDP's) are significantly modified, the total electron content (TEC) is altered, and enhanced plasma transport occurs. These physical effects have been observed by rocket and satellite measurements for many years. We developed a new fluid theory for the auroral return-current region in the guiding-center and gyrotropic approximation,

including the effect of wave-particle interactions due to plasma turbulence.

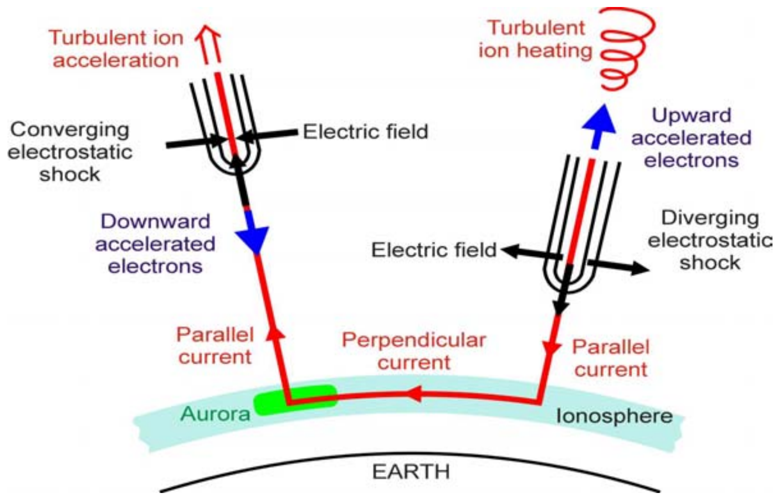

Figure 3. Field-aligned (Birkeland) Currents in the Earth's Magnetosphere.

The equations of the theory are based on the Vlasov-Maxwell equations for the particle dynamics and a Fokker-Planck model for the wave-particle interactions. They describe how magnetospheric disturbances affect the ionospheric plasma properties such as density, temperature and drifts. The fluid equations can be solved (1) by using measurements of the turbulence to specify the electric field fluctuations; and (2) by using measurements of the low-order velocity moments to specify the initial and boundary conditions. The theory produced the first results for the auroral return-current region that agreed with the FAST and Interball satellite wave and particle data. Early work by other research groups on the auroral return-current region was unsatisfactory and predicted parallel E-fields that were three orders of magnitude too small. We found that on geomagnetic flux tubes at the bottom of the acceleration region in the inner magnetosphere, a plasma double layer (DL) forms that accelerates electrons away from the earth and ions towards the earth. A transition region (TR) forms just above the DL where the plasma turbulence is very intense, the electron beam generated by the DL is thermalized, and the ions are

heated perpendicular and parallel to the geomagnetic field by wave-particle interactions. Above the TR is the long range potential region (LRPR) extending from the top of the TR to several earth radii and beyond. In this region, the field-aligned potential increase is about 3 to 4 times the potential increase in the DL. These results agree with satellite observations.

2.6. Turbulent Heating of Magnetospheric Ions in Downward Birkeland Current Regions [*Jasperse et al.*, 2006]

We developed a new fluid theory in the guiding-center and gyrotropic approximation that includes the effect of wave-particle interactions due to plasma turbulence. We used the theory for quasi-steady conditions to derive: (1) a new formula for the perpendicular ion-heating rate per unit volume; and (2) a new formula for the perpendicular ion temperature profile at low altitudes in the downward Birkeland current region. We found that the ion-heating rate does not increase indefinitely as the distance along the magnetic field line increases, rather, it is reduced by the finite gyroradius effect. The results of the calculations are consistent with the satellite observations.

2.7. A Comparative Study of Different Theoretical Descriptions of Linear Equatorial Plasma Instability [*Basu*, 2002]

The so-called ‘bubbles’ and ‘plumes’ that are observed in the nighttime equatorial ionosphere are the fully developed nonlinear state of a plasma instability, driven by the combined effects of gravity, eastward electric field and vertically downward neutral wind in the presence of a vertically upward density gradient. A nonlinear theory is required to explain these observations. However, the linear theory is useful for understanding the basic physical mechanism for the instability and for the characteristic properties of the excited plasma modes. In addition, the growth rates obtained from the linear theory can be used to specify/predict the

region of the equatorial ionosphere where ‘bubbles’ and ‘plumes’ may be expected. Plasma turbulence inside the ‘bubbles’ and ‘plumes’ causes scintillation of radio signals traversing them and can lead to communication outage. Thus, accurate calculation of linear growth rates is important for the space weather specification and forecasting system (C/NOFS), and, hence, a physically accurate model for the linear stage of the instability should be adopted for the calculation of the growth rates.

In the literature, there are three theoretical descriptions of the linear equatorial plasma instability. These three descriptions are: local description, flux-tube-integrated description, and ballooning-mode type description. By using a realistic model ionosphere and neutral atmosphere, we calculated the relevant plasma parameters and then evaluated the growth rates and other characteristics of the plasma instability that are obtained from the three descriptions. Comparison shows that the ballooning-mode type description, developed at AFRL, gives a physically more accurate and more complete description of the equatorial plasma instability and thus should be adopted for the calculation of the linear growth rates.

2.8. Characteristics of Electromagnetic Rayleigh-Taylor Modes in Nighttime Equatorial Plasma [*Basu*, 2005]

The unstable Rayleigh-Taylor plasma modes that are believed to be responsible for the density irregularities in the nighttime *F* region equatorial ionosphere have been studied before by assuming that the modes are electrostatic. In this work, the unstable plasma modes are studied without this assumption to determine the strength and the characteristics of the magnetic field fluctuations and to determine the physical condition under which the electrostatic assumption is

justified. It is found that the relevant magnetic field fluctuations ($\tilde{B}_\rho$), which arise from the fluctuating parallel (to $\mathbf{B}_0$) current density, are associated with the shear Alfven waves. The parameter that determines the amplitude of $\tilde{B}_\rho$ is $\alpha(s) \equiv D_m(s)\, k_\varphi^2\,/\gamma$, where $D_m(s)\, k_\varphi^2$ represents the rate at which magnetic field fluctuations with perpendicular wavelength λ_φ ($\equiv 2\pi/ k_\varphi$) diffuse away due to parallel resistivity and γ is the rate at which the fluctuations grow. Typically, $\alpha >> 1$ in the equatorial ionosphere, which means that the excited magnetic field fluctuations diffuse at a rate much faster than their growth rate and, consequently, their amplitudes remain very small (compared to B_0). Thus the Rayleigh-Taylor modes in the equatorial ionosphere are predominantly electrostatic in nature, and the electrostatic assumption of the previous analyses is quite justified. If the maximum amplitude of the electric field fluctuations ($\tilde{E}_\varphi$) is taken to be 1 mV/m, then the maximum amplitude of $\tilde{B}_\rho$ is found to be less than 0.2 nT when λ_φ is 500 m, and it increases to about 2.4 nT when λ_φ is 20 km. Longer wavelength modes have somewhat larger magnetic field fluctuations, but their growth rates are smaller. While the maximum amplitude of $\tilde{E}_\varphi$ occurs at the magnetic equator, that of $\tilde{B}_\rho$ occurs at a distance away from it.

2.9 New Model for Predicting the Strength of Equatorial Scintillations [*Retterer et al.*, 2005]

One of the regions where the ionosphere has its greatest impact on operational systems is the equatorial zone, where scintillations caused by plasma turbulence frequently but unpredictably cause outages of communication and navigation systems dependent on radio links. To address this environmental hazard, AFRL has initiated the C/NOFS project to provide forecasts of the locations, times, and durations of these outages. Although the engineering of the

satellite hardware for the project is fairly straightforward, the science of intrepreting the observations and using them to make forecasts of ionospheric activity remains on the forefront of basic research. Using data from the Jicamarca Radar Observatory, we have shown that by assimilating knowledge of the vertical drift of the plasma after sunset into an ionospheric forecast model, we can make a prediction for the strength of the growth rates of the Rayleigh-Taylor instability of the plasma that correlates well with the detection of scintillation. Analyzing a set of seven cases, we found that the case with the lowest growth rate had the weakest scintillation, the case with the largest growth rate was an event of strong equatorial bubbles, and the intermediate growth-rate events had spread-F of intermediate strength.

The implication for the success of the C/NOFS program is immediate. If the sensors onboard the C/NOFS satellite can give us the information we need to make a good prediction of the strength of the vertical velocity after sunset, then with our theoretical models, we will be able to make a reliable prediction of the likelihood of scintillation in that sector.

2.10. Forecast Model of Equatorial Radio Scintillation [*Retterer*, 2005]

Based on the expectation that detailed knowledge of the ionospheric structure would allow us to know where the plasma would be unstable, and therefore would allow the formation of scintillation-producing turbulence, we have designed and implemented a software system to use the data returned by the C/NOFS satellite to produce a forecast of scintillation occurrence in real time using first-principles physics models of the ionosphere. In analogy to tropospheric weather forecasting, the system assimilates data from the satellite to provide a snapshot of the current conditions in the ionosphere. This provides an initial condition for the integration of the fluid equations that describe the evolution of the ionospheric plasma density. As the plasma density evolves, its structure is examined for conditions under which the Rayleigh-Taylor instability will

operate. At those places that are unstable, a mesoscale model for the development of plasma turbulence is launched to determine the statistical characteristics of the turbulence, which are used in a phase-screen model to determine the impact on radio links of the scintillation caused by the turbulence. Figure 4 shows the system components and the information flows among them.

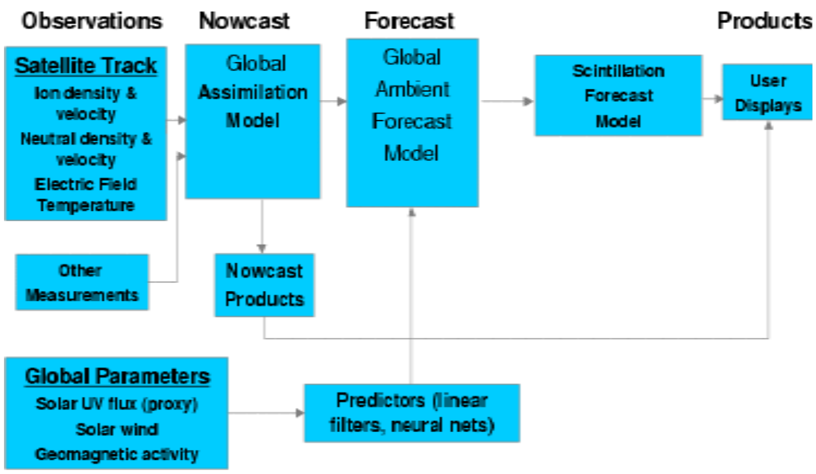

Figure 4. Overall Organization of the Forecasting System.

From its crude beginnings, the forecast capability of this system has improved greatly, much as the result of work spurred on by deficiencies noted in validation exercises. A partial list of these exercises include: test plasma velocity vs. Jicamarca ISR, F layer height vs. ionosonde, plasma density profiles vs. Jicamarca ISR, correlation between RT growth rate and bubbles, in-situ plasma density vs. CHAMP, in-situ plasma density vs. DMSP, Total Electron Content vs. Jason, plasma density profiles vs. ionosonde, scintillation climatology, bubble climatology vs. DMSP statistics, airglow depletions vs. TIMED GUVI observations, scintillation strength vs. SCINDA measurements, and scintillation strength vs. ROCSAT in-situ irregularities.

2.11. Modeling the Connection of the Global Ionospheric Electric Fields to the Solar Wind [*Rothwell and Jasperse*, 2006]

A global ionospheric electrostatic potential model, which we refer to as Nopper-

Carovillano [N-C], can be linked with a magnetospheric potential model. The latter model, which we refer to as Hill-Siscoe-Ober [H-S-O], computes a transpolar potential Φ_{PC} (H-S-O) based on solar wind parameters and Region-1 field-aligned currents (FAC) from the magnetosheath to the ionosphere. The polar ionospheric conductance required by H-S-O is defined by the N-C model. In this way, the transpolar potential and the associated FAC are the same in both models. A distribution of Region-1 FAC in the N-C model predicts a two-cell convection pattern which is in reasonable agreement with plasma drifts measured by DMSP (Defense Meteorological Satellite Program) satellites. The H-S-O model, as modified by N-C, is compared with the Weimer potential model and with the transpolar potentials observed by DMSP satellites during the 6-7 April 2000 magnetic storm. Good agreement is found in both cases. The Region-2 (J2) current is estimated from the Siscoe (S-RC) ring-current circuit model which is driven by Φ_{PC} (H-S-O). The resistor values in S-RC, as determined by N-C, when combined with the global potential solution, make it possible to estimate the time profile of the equatorial penetration electric field during the storm's main phase. With the values obtained, shielding occurs within 1 h of onset. Equatorial plasma bubbles (EPBs) are seen ~ 1 h after the initial increase of Φ_{PC} and are qualitatively consistent with the equatorial penetration electric field calculated by the combined model.

2.12. A Coupled Solar wind-Magnetosphere-Ionosphere Model for Determining the Ionospheric Penetration Electric Field [*Rothwell and Jasperse*, 2007]

The transpolar potential Φ_{PC} may be estimated from the solar wind as measured by the ACE (Advanced Composition Explorer) satellite at the first Lagrangian point L1. In our model, the transpolar potential drives the region-1 (J1) currents through the ionosphere consistent with a solar-dependent ionospheric conductance. It is shown that the ionospheric potential may be

derived from an equivalent Poisson equation, the solution of which gives the global distribution of the ionospheric electric field, including the penetration electric field near the equator. This eastward penetration electric field just past sunset, which is created by J1, is offset by a region-2 (J2) generated westward (shielding) electric field with an unknown rise time. We find that there is a correlation between storm-time potential enhancements and the presence of equatorial bubbles as measured on DMSP satellites. The magnetic storms of 6-7 April 2000 and 20-21 November 2003 were analyzed. In both cases, the observed presence of equatorial plasma bubbles showed better agreement with model predictions using a longer J2 rise time.

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APPENDIX

LIST OF ALL PUBLICATIONS DURING THE FIVE-YEAR TASK PERIOD

(Names of Task Members are in Bold Faces)

Basu, B., On the linear theory of equatorial plasma instability: Comparison of different descriptions, *J. Geophys. Res.*, **107**, A8, doi:10.1029/2001JA000317, 2002.

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